

Condensation Behavior in Warmly Packaged Pet Food Pellets

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Introduction

Packaging warm, dried products can result in some condensation in the package, even though the products were dried. Higher localized moistures then provide the opportunity for mold growth, thereby spoiling the product. This is a typical problem in dry pet food processing. Here product is extruded, expanded and formed into kibbles. The product is then dried and coated with hot fat and with liquid flavors. From there it travels through retention bins and on to packaging. Sometimes process and environmental conditions are such that condensation does not occur. Sometimes conditions allow condensation to form, but the moisture then reabsorbs back into the product before significant mold growth occurs. Sometimes there's a problem.

Manufacturers often include coolers or provide an opportunity for ventilation in the process stream prior to packaging. Over design, and some experience, usually deliver a process system that avoids the problem. However, efficient design requires a more quantitative understanding of the phenomena. This paper presents an example of how this was attempted.

Description of the Phenomena

Our problem occurs in a sealed package. What happens inside that package is a function of the physical properties of the kibble entering that bag, and also the environmental conditions that the bag is exposed to. The vapor barrier characteristics of the package also play a role. Our example deals with multilayer paper bags with a plastic liner. Many manufacturers use plastic bags. In either case, the moisture barrier is quite good and the rate of moisture loss is slow.

To describe our problem then, we need to consider the following effects, from which we attempt to model our system:

- Bag cooling curves (inside bag surface and product temperatures),
- Internal bag humidity changes as a function of time,
- Internal bag humidity changes and equilibrium humidity as a function of temperature,
- The effect of product moisture on internal bag humidity.

First we try to understand how the surface temperature of the inner bag liner changes over time. This is where condensation will occur. Although it takes a bit of work, experiments to determine how this temperature changes as a function of product pack temperature and external temperature are easy enough to do. The problem gets a bit complicated when we realize that product is stored on pallets and that every bag will behave differently. If we focus on the bag and the bag surface that cools most quickly, our analysis will provide information on the worst case.

Figure 1 illustrates the temperature decay observed at various pallet locations for a given product pack temperature and room temperature. The lower curves are obviously taken from bags at the pallet edge, while the upper curves are taken closer to the pallet center.

Curves are also taken, within a given bag, at the bag liner surface and product center. In this particular example, product was packed at 50 C (about 122 F) and stored at 27 C (about 80 F).

This problem is an unsteady state heat conduction problem. General solutions for one-dimensional conduction tend to be exponential series functions. If we consider the variable $(T-T_s)/(T_o-T_s)$, where T_s and T_o are the outside and initial temperatures respectively, we see that this temperature decay can be modeled with the equation

$$T = T_s + (T_o - T_s) \exp(-kt) \tag{1}$$

where k would be an apparent thermal conductivity at the point in question.

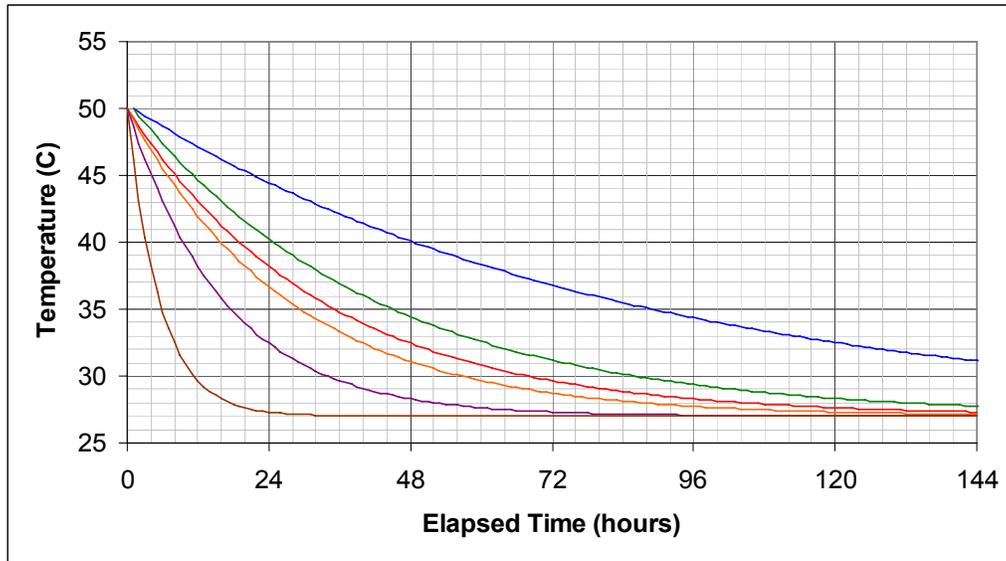


Figure 1: Temperature Decay at Various Pallet and Bag Positions

Figure 2 shows the plot of $\ln(T-T_s)/(T_o-T_s)$ as a function of time. The behavior is linear, as expected, and an apparent thermal conductivity can be determined from the slope.

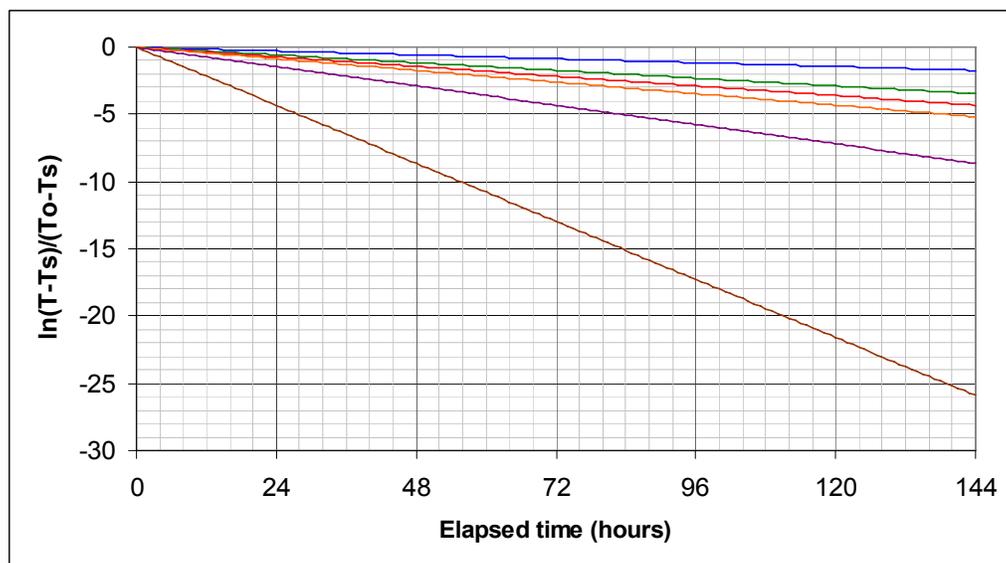


Figure 2: $\ln(T-T_s)/(T_o-T_s)$ as a Function of Time

By conducting several experiments at different pack and storage temperatures, and by looking at different pallet configurations, we can identify the configuration that presents the worst-case situation. The subsequent analysis can then focus on that configuration.

Table 1 shows the apparent thermal conductivities determined by experiment at various pallet positions. Because the physical system is so complex, these are crude empirical constants. However, for a fixed configuration they are consistent and do allow us to predict behavior. Our worst-case is chosen at the outer edge for the 4 base x 7 high pallet configuration.

Table 1: Apparent Thermal Conductivities at Various Pallet Positions

k (1/min.)	4 Bag Base x 7 Bag High Pallet Configuration
0.000727	Top Row - Bag Liner
0.002760	Outside Edges - Bag Liner
0.000956	Bottom Row by Cement - Bag Liner
0.000352	Product Core - Outside Bag
	5 Bag Base x 13 Bag High Configuration
0.000531	Top Row - Bag Liner
0.000915	Bottom Row by Cement - Bag Liner
0.000215	Product Core - Botton Row

Next we need to understand the humidity inside the bag. This is going to be a function of the moisture and temperature of the product. Making use of remote recording equipment (Veriteq Spectrum 2000 data loggers were used), we can place a sensor in the bag immediately after filling. We then record the temperature and humidity changes over time as the palletized bag sits in storage. Figure 3 shows an example of the relative humidity behavior. Here bags were packed at the same temperature, but held at different conditions.

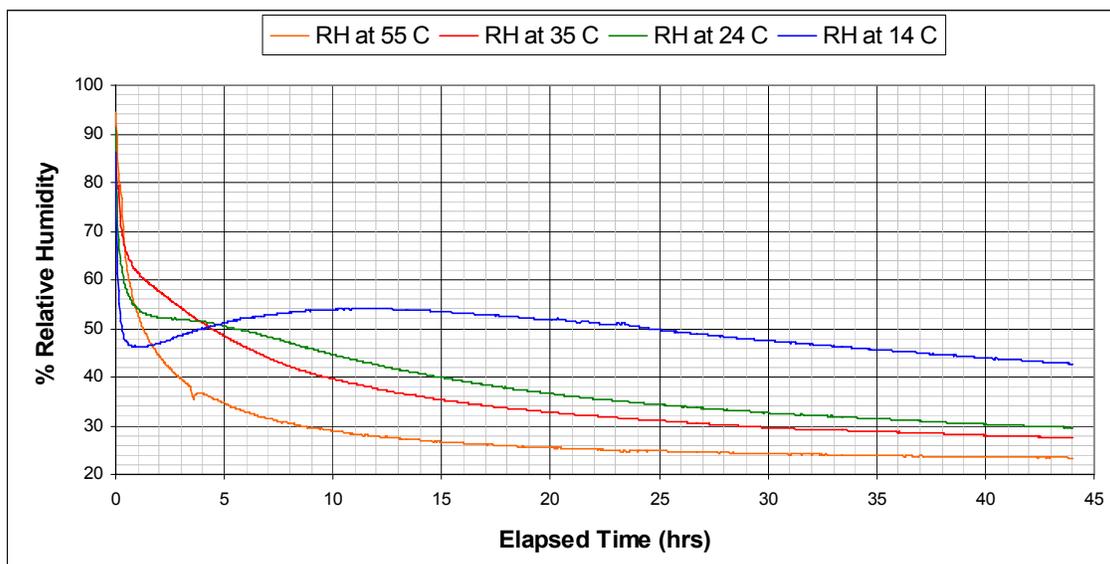


Figure 3: Relative Humidity Decay as a Function of Environmental Temperature

The initial humidity in the bag is much higher than the equilibrium relative humidity of the product. The decay curve is complex. Both temperature effects and mass transfer, or equilibration effects, are expected. In the case of colder environmental temperatures an odd increase in humidity is seen, after which the decay continues. Physical examination of the bags confirms condensation occurred at both the 24 C and 14 C ambient condition. The inversion of the relative humidity decay curve coincides with that observation. At warmer environmental temperatures the decay is steady, but it does not follow simple first order behavior. The experiment at 55 C was basically an isothermal experiment and allows us to take a closer look at the relative humidity decay with time. Here we learn that the humidity decay observes 2nd order behavior. This is shown in Figure 4.

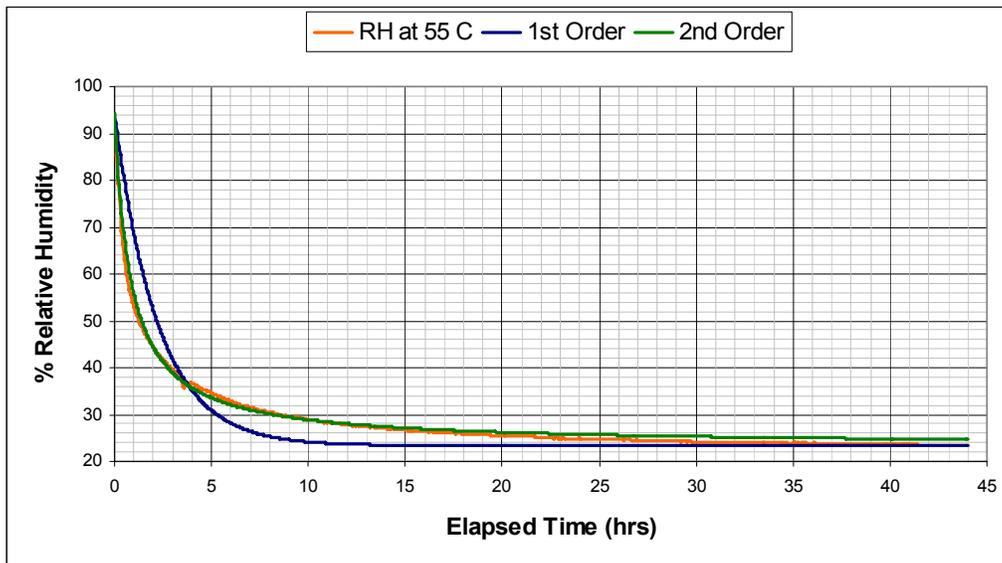


Figure 4: Isothermal Humidity Decay in Comparison to 1st and 2nd Order Models

This second order decay can be described by the equation

$$\frac{dh}{dt} = Kh^2 \quad (2)$$

where h is the relative humidity of the vapor space, t refers to time and K is an observed mass transfer coefficient. Solving for h with respect to time results in

$$h(t) = h_e + \frac{1}{Kt + \frac{1}{(h_o - h_e)}} \quad (3)$$

Subscripts o and e refer to initial and equilibrium conditions respectively.

This seems to work well for the isothermal example. For the non-isothermal case this model is not quite right. An additional correction is required. Examining the product equilibrium relative humidity offers some insight into what might be happening. Equilibrium relative humidity is studied as a function of moisture at a constant temperature. This work is usually done at a standard temperature of 20 C. We needed to do this to determine the value of h_e for product in our study. However, temperature also has an affect on equilibrium relative humidity. An Arrhenius relationship is expected, but in our case a linear relationship seems to

fit the data well enough. It also appears that the effect of temperature is constant as moisture changes. This temperature effect is illustrated in Figure 5.

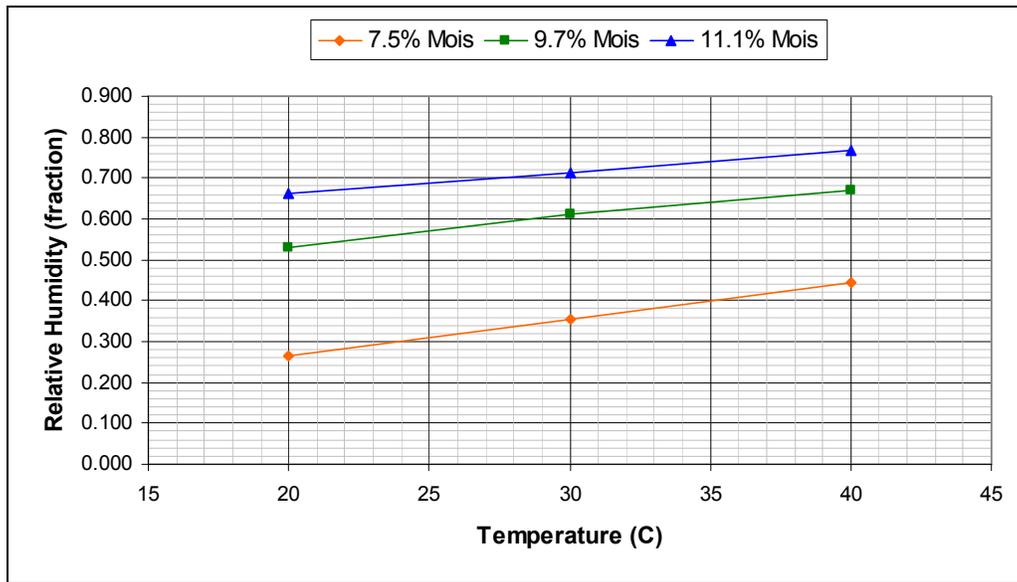


Figure 5: Product Equilibrium Relative Humidity at various Temperatures and Moistures.

This temperature correction would then take the form

$$h(T) = K_T(T - T_e) + h_e \quad (4)$$

Where T refers to temperature, e refers to a reference equilibrium condition and K_T is the thermal correction coefficient. If we substitute this corrected equilibrium humidity term into equation (2) we arrive at a new expression for relative humidity as a function of temperature and time.

$$h(t, T) = K_T(T - T_e) + h_e + \frac{1}{Kt + \frac{1}{(h_o - K_T(T - T_e) - h_e)}} \quad (5)$$

The form of this equation fits our data very well. We can use the same observed mass transfer coefficient arrived at in our isothermal experiment. The equilibrium humidity and temperature are product physical properties. From our experiments illustrated in Figure 5 we have a value for the thermal correction coefficient. Our non-isothermal experiment humidity decay curve is show in Figure 6 and compared to the prediction obtained using Equation (2), without the temperature correction, and equation (4), with the temperature equation. There is no regression involved. The constants used were obtained from prior experiments. Equation (4) seems to do the job.

Our last task is to define the equilibrium humidity of the product involved. This is easy to do in the lab. Specific equipment exists for this purpose. The data can be represented using a logarithmic equation of the form

$$h_e = A \ln(M) + B \quad (6)$$

where A and B are regression constants, and M is the product moisture.

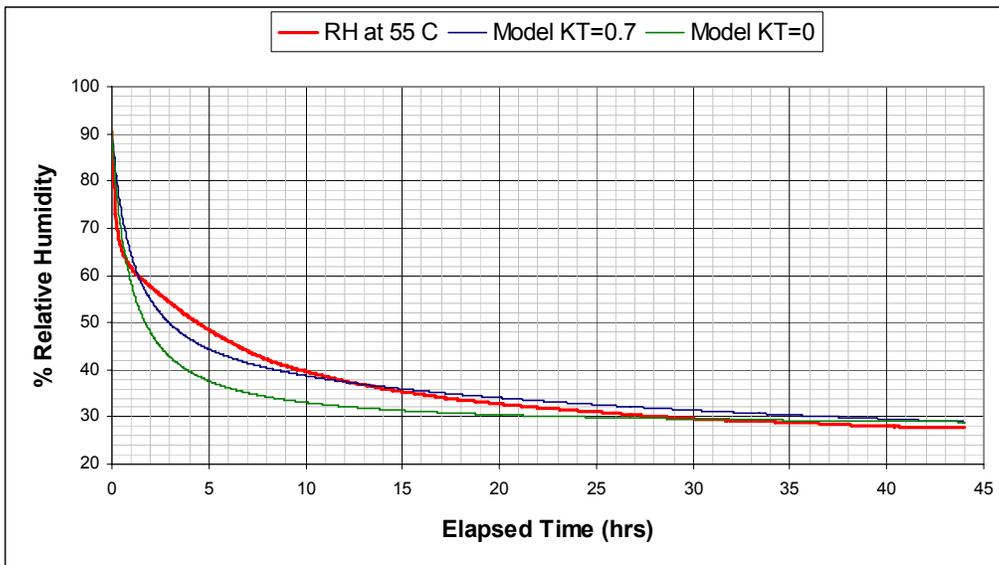


Figure 6: Non-Isothermal Humidity Decay and 2nd Order Models with and without Temperature Compensation

One of our product humidity curves is shown in Figure 7. These do tend to vary from product to product. However, similar products behave very much the same. It's easy enough to make these measurements on a range of products and then select the product with the highest humidity curve for subsequent process analysis work. This will be the worst case.

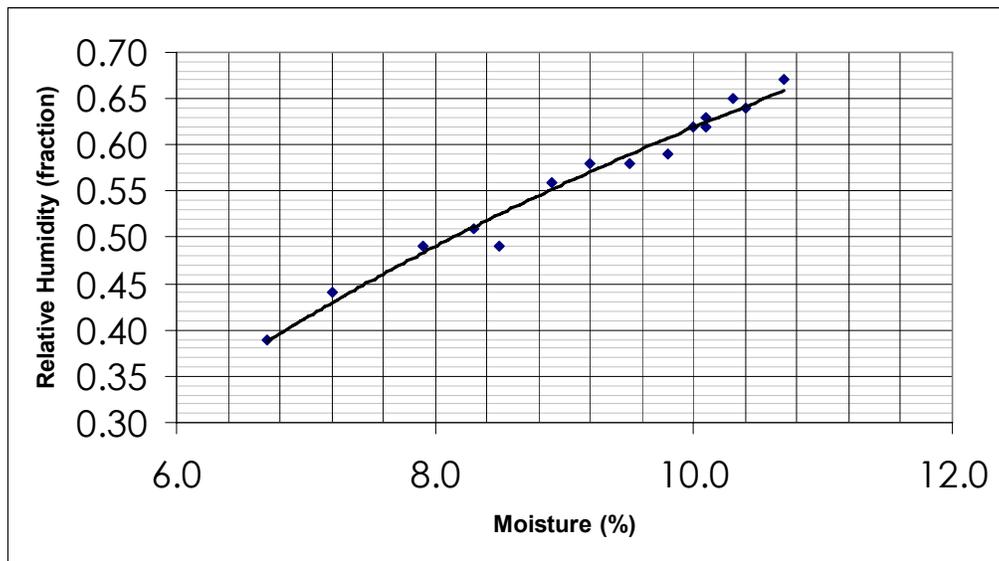


Figure 7: Product Equilibrium Relative Humidity as a Function of Moisture at 20 C

Now that we've described the phenomena we believe are involved, we can assemble the pieces needed to model the system.

The Model

The first step will be to calculate the product temperature as a function of time. The inputs needed are the bag pack temperature, the apparent product (or “bag”) thermal conductivity and the storage temperature. A time interval is chosen, and the calculation is done for each interval.

Next the bag liner surface temperature is calculated in the same way. The only difference is that the thermal conductivity used is now that for the inside bag surface. Experimental values are selected, for both the bag and the product, based on what we have found our worst case to be.

Humidity is calculated next. To do this we rely on Equation (5). The required inputs are K , the observed mass transfer coefficient, K_T , the thermal correction coefficient, h_e and T_e , the product equilibrium humidity and corresponding temperature, and h_o , the initial humidity in the bag. Now this is a problem. We don't necessarily know the initial relative humidity. However, from our earlier experiments we know that this ranged from 85% to 95% for all the pack temperatures and moistures we've examined. We can use the 95% value for our worst case analysis. The product equilibrium relative humidity must be calculated from the product moisture using Equation (6).

Finally a dew point temperature is calculated and compared to the bag inner liner temperature. If the bag liner surface temperature is below the dew point, moisture will condense at the surface. This is the condition we wish to avoid. The method for dew point calculation is that used by the portable humidity meter manufacturer (Veriteq Spectrum 2000 data loggers were used) and is based on the Magnus-Tetens formula.

$$T_d = \frac{237.7\alpha}{17.27 - \alpha} \quad (7)$$

Where α is defined as

$$\alpha = \frac{17.27T}{237.7 + T} + \ln(h) \quad (8)$$

and T is the temperature in degrees C with h the % relative humidity.

Calculation Examples

Our first example should be one that matches an actual experiment done. We can run through the calculations, and then examine some pallets and bags to see if the condensation behavior matches what is predicted. In this example, bags are packed at 55 C and 9% moisture, and the ambient storage temperature is 20 C. Our selection of physical properties and conditions are given in Table 2.

Prod Thermal k (/min)	0.00035	Eq. Hum. A	0.59	at 20C
Bag Thermal k (/min)	0.00276	Eq. Hum. B	-0.73	
Pack T (C)	35.0	Mois (%)	7.00	
Ambient Temp (C)	20.0	h e (%)	41.2	
Mass Transfer K (/min)	0.00028	h o (%)	95.0	
Thermal Coef KT (%/C)	0.71			

Table 2: Physical Properties and Conditions for Calculation Example

Running through the calculations, we see that the bag liner temperature drops below the dew point at approximately 18 minutes after filling and placing the pallet in its storage area. Observation confirms the presence of moisture within the first half hour. Calculation results are shown in Table 3.

Time Since Pack (hrs)	t (min)	Prod T (C)	RH	Dew Pt (F)	Bag T (F)	delta
0	0	55.0	95.0	53.9	55.0	1.1
0.1	6	54.9	94.7	53.8	54.4	0.6
0.2	12	54.9	94.4	53.6	53.9	0.2
0.3	18	54.8	94.0	53.5	53.3	-0.2
0.4	24	54.7	93.7	53.4	52.8	-0.6
0.5	30	54.6	93.4	53.2	52.2	-1.0

Table 3: Dew Point Calculation Results for 55 C Pack Temperature, 20 C Ambient Storage Temperature and 9% Product Moisture.

Now we can begin to examine what conditions might be required to avoid condensation. The onset of condensation can be delayed by reducing product moisture or pack temperatures. If sufficient reductions are implemented, condensation can be avoided altogether. For example, a moisture of 7% and a pack temperature of 35 C avoids the problem. The calculation details are given in Table 4. Other options might be to reduce the initial relative humidity by providing some product retention with ventilation.

Time Since Pack (hrs)	t (min)	Prod T (C)	RH	Dew Pt (F)	Bag T (F)	delta
0	0	35.0	95.0	34.1	35.0	0.9
2	120	34.4	69.1	27.9	30.8	2.9
4	240	33.8	62.1	25.5	27.7	2.2
6	360	33.2	58.7	24.0	25.6	1.5
8	480	32.7	56.6	22.9	24.0	1.1
10	600	32.1	55.1	22.0	22.9	0.9
12	720	31.6	54.0	21.2	22.1	0.9
14	840	31.2	53.0	20.4	21.5	1.0
16	960	30.7	52.3	19.8	21.1	1.3
18	1080	30.3	51.6	19.2	20.8	1.6
20	1200	29.8	51.0	18.6	20.5	2.0

Table 4: Dew Point Calculation Results for 35 C Pack Temperature, 20 C Ambient Storage Temperature and 7% Product Moisture.

It is important to remember that we did not model the inflection seen in the humidity decay curve during condensation. These equations appear valid when condensation does not occur. We should be able to predict the onset of condensation. However, the model is expected to fail after that point.